Multi-Hazard Flooding Interactions in the Ōpāwaho Heathcote Catchment, Christchurch, New Zealand

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UC ICRG Report 02-17

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Extreme flooding in the lower Ōpāwaho Heathcote catchment March 2014, post the Canterbury Earthquake Sequence (CES). Photograph taken by Marney Brosnan.

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UC ICRG Report 11-16

1. Executive summary

This report provides an initial overview and gap analysis of the multi-hazards interactions that might affect fluvial and pluvial flooding (FPF) hazard in the Ōpāwaho Heathcote catchment. As per the terms of reference, this report focuses on a one-way analysis of the potential effects of multi-hazards on FPF hazard, as opposed to a more complex multi-way analysis of interactions between all hazards. We examined the relationship between FPF hazard and hazards associated with the phenomena of tsunamis; coastal erosion; coastal inundation; groundwater; earthquakes; and mass movements.

Tsunamis: Modelling research indicates the worst-case tsunami scenarios potentially affecting the Ōpāwaho Heathcote catchment are far field. Under low probability, high impact tsunami scenarios waves could travel into Pegasus Bay and the Avon-Heathcote Estuary Ihutai, reaching the mouth and lower reaches of the Heathcote catchment and river, potentially inundating and eroding shorelines in sub-catchments 1 to 5, and temporarily blocking fluvial drainage more extensively. Any flooding infrastructure or management actions implemented in the area of tsunami inundation would ideally be resilient to tsunami-induced inundation and erosion. Model results currently available are a first estimate of potential tsunami inundation under contemporary sea and land level conditions. In terms of future large tsunami events, these models likely underestimate effects in riverside sub-catchments, as well as effects under future sea level, shoreline and other conditions. Also of significance when considering different FPF management structures, it is important to be mindful that certain types of flood structures can 'trap' inundating water coming from ocean directions, leading to longer flood durations and salinization issues.

Coastal erosion: Model predictions indicate that sub-catchments 1 to 3 could potentially be affected by coastal erosion by the timescale of 2065, with sub-catchments 1-6 predicted to be potentially affected by coastal erosion by the time scale of 2115. In addition, the predicted open coast effects of this hazard should not be ignored since any significant changes in the New Brighton Spit open coast would affect erosion rates and exposure of the landward estuary margins, including the shorelines of the Ōpāwaho Heathcote catchment. Any FPF flooding infrastructure or management activities planned for the potentially affected sub-catchments needs to recognise the possibility of coastal erosion, and to have a planned response to the predicted potential shoreline translation.

Coastal inundation: Model predictions indicate coastal inundation hazards could potentially affect sub-catchments 1 to 8 by 2065, with a greater area and depth of inundation possible for these same sub-catchments by 2115. Low-lying areas of the Ōpāwaho Heathcote catchment and river channel that discharge into the estuary are highly vulnerable to coastal inundation since elevated ocean and estuary water levels can block the drainage of inland systems, compounding FPF hazards. Coastal inundation can overwhelm stormwater and other drainage network components, and render river dredging options ineffective at best, flood enhancing at worst. A distinction can be made between coastal inundation and coastal erosion in terms of the potential impacts on affected land and assets, including flood infrastructure, and the implications for acceptance, adaptation, mitigation, and/or modification options. That is, responding to inundation could include structural and/or building elevation solutions, since unlike erosion, inundation does not necessarily mean the loss of land.

Groundwater: Groundwater levels are of significant but variable concern when examining flooding hazards and management options in the Ōpāwaho Heathcote catchment due to variability in soils, topographies, elevations and proximities to riverine and estuarine surface waterbodies. Much of the Canterbury Plains part of the Ōpāwaho Heathcote catchment has a water table that is at a median depth of <1m from the surface (with actual depth below surface varying seasonally, inter-annually and during extreme meteorological events), though the water table depth rapidly shifts to >6m below the surface in the upper Plains part of the catchment (sub-catchments 13 to 15). Parts of Waltham/Linwood (sub-catchments 5 & 6) and Spreydon (sub-catchment 10) have extensive areas with a particularly high water table, as do sub-catchments 18, 19 and 20 south of the river. In all of the sub-catchments where groundwater depth below surface is shallow, it is necessary to be mindful of cascading effects on liquefaction hazard during earthquake events, including earthquake-induced drainage network and stormwater infrastructure damage. In turn, subsidence induced by liquefaction and other earthquake processes during the CES directly affected groundwater depth below surface across large parts of the central Ōpāwaho Heathcote catchment. The estuary margin of the catchment also faces increasing future challenges with sea level rise, which has the potential to elevate groundwater levels in these areas, compounding existing liquefaction and other earthquake associated multi-hazards. Any increases in subsurface runoff due to drainage system, development or climate changes are also of concern for the loess covered hill slopes due to the potential to enhance mass movement hazards.

Earthquakes: Earthquake associated vertical ground displacement and liquefaction have historically affected, or are in future predicted to affect, all Ōpāwaho Heathcote sub-catchments. During the CES, these phenomena induced a significant cascades of changes in the city's drainage systems, including: extensive vertical displacement and liquefaction induced damage to stormwater 'greyware', reducing functionality of the stormwater system; damage to the wastewater system which temporarily lowered groundwater levels and increased stormwater drainage via the wastewater network on the one hand, creating a pollution multi-hazard for FPF on the other hand; liquefaction and vertical displacement induced river channel changes affected drainage capacities; subsidence induced losses in soakage and infiltration capacities; changes occurred in topographic drainage conductivity; estuary subsidence (mainly around the Ōtākaro Avon rivermouth) increased both FPF and coastal inundation hazards; estuary bed uplift (severe around the Ōpāwaho Heathcote margins), reduced tidal prisms and increased bed friction, producing an overall reduction the waterbody's capacity to efficiently flush catchment floodwaters to sea; and changes in estuarine and riverine ecosystems. All such possible effects need to be considered when evaluating present and future capacities of the Ōpāwaho Heathcote catchment FPF management systems. These phenomena are particularly of concern in the Ōpāwaho Heathcote catchment since stormwater networks must deal with constraints imposed by stream and river channels (past and present), estuarine shorelines and complex hill topography.

Mass movements: Mass movements are primarily a risk in the Port Hills areas of the Ōpāwaho Heathcote catchment (sub-catchments 1, 2, 7, 9, 11, 16, 21), though there are one or two small but susceptible areas on the banks of the Ōpāwaho Heathcote River. Mass movements in the form of rockfalls and debris flows occurred on the Port Hills during the CES, resulting in building damage, fatalities and evacuations. Evidence has also been found of earthquake-triggered tunnel gully collapses in all Port Hill Valleys. Follow-on effects of these mass movements are likely to occur in major future FPF and other hazard events.

Of note, elevated groundwater levels, coastal inundation, earthquakes (including liquefaction and other effects), and mass movement exhibit the most extensive levels of multi-hazard interaction with FPF hazard. Further, all of the analysed multi-hazard interactions except earthquakes were found to consistently produce increases in the FPF hazard. The implications of these analyses are that multi-hazard interactions generally enhance the FPF hazard in the Ōpāwaho Heathcote catchment. Hence, management plans which exclude adjustments for multi-hazard interactions are likely to underestimate the FPF hazard in numerous different ways.

In conclusion, although only a one-way analysis of the potential effects of selected multi-hazards on FPF hazard, this review highlights that the Ōpāwaho Heathcote catchment is an inherently multi-hazard prone environment. The implications of the interactions and process linkages revealed in this report are that several significant multi-hazard influences and process interactions must be taken into account in order to design a resilient FPF hazard management strategy.

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2. Background

Christchurch City Council has engaged Jacobs to investigate and develop a Floodplain Management Strategy for the Heathcote River. Flooding is interpreted in this context to mean fluvial and pluvial flooding (FPF) within the catchment, and to exclude other forms of flooding such as that induced by tsunami inundation, or by coastal inundation as a result of sea level rise. The wider report includes a gap analysis, gap filling and development of global catchment wide and local options to address specific FP flooding concerns.

The present University of Canterbury research report sits within the wider FPF options assessment, and focusses on relevant information concerning non-FPF multi-hazards that have the potential in some way to affect the resilience, appeal, cost or design standards of FPF management options.

'Multi-hazard' in the context of this report means any non-FPF hazard which has the potential to influence the amount of flooding across any part of the Ōpāwaho Heathcote Catchment. Non-FPF multi-hazards reviewed in this report include natural hazards associated with the phenomena of:

1. tsunamis;
2. coastal erosion;
3. coastal inundation;
4. groundwater table rise;
5. earthquakes, including vertical displacement and liquefaction; and
6. mass movements, including rapid soil erosion.

Tsunamis are displacement waves, created when a large volume of ocean or lake water is suddenly displaced, for example, by earthquakes, volcanic eruptions, and terrestrial or underwater landslides, or meteorite impacts. Tsunami waves have long wave lengths, and low amplitudes in deep waters with their amplitudes growing during shoaling in shallow nearshore environments. The extent of inundation, erosion and other kinds of damage experienced in a particular event is a function not only of the wave characteristics (e.g. velocities, amplitudes, number and timing of large waves), but also of tidal and meteorological conditions (storm surge, river levels), and of nearshore, beach backshore and river topography (Hart and Knight 2009).

Coastal erosion is the process of wearing away and removing sediment and other materials from a particular coastal environment. On unconsolidated shores, such as along the majority of the Avon-Heathcote Estuary Ihutai shoreline, this process results from an imbalance in the supply and export of materials to a particular section of coast or 'coastal cell'. Coast erosion can occur during everyday conditions, during high tide and storm conditions, and/or as a response to long-term changes in sea levels. Coastal erosion may be expressed in terms of volume of material removed per length of coast per unit of time (e.g. m^3/m/year). Where it impacts the shoreline position, the term coastal erosion is often used synonymously with 'shoreline retreat', as in the case of the Tonkin and Taylor (2015) results reproduced in this multi-hazards analysis (e.g. m/year).

Coastal inundation is generally defined as flooding by the sea. Excluding inland coasts like lakes, areas affected by coastal inundation are flooded with seawater, bringing the dual challenges of water and salt, with wave and current induced effects like erosion also possible. Coastal inundation occurs on extreme high tides, with storm surges and/or with large waves, and is forecast to occur more frequently, severely and extensively in future as a result of sea level rise and increases in storm intensity. The coastal inundation results used in the present multi-hazards analysis comprise future predictions based on an IPCC sea level rise scenario.

Figure 1. FPF flood hazard enhanced by CES indiced changes to topography and stormwater systems

Figure 2. CES indiced drainage estuary margin damage in the Ōpāwaho Heathcote catchment

Of significance for the Ōpāwaho Heathcote catchment, areas where rivers or creeks meet the sea are more vulnerable to coastal inundation since high seas can cause the rivers to back up inland. Coastal inundation can also cause stormwater and drainage network components to be overwhelmed and rendering river dredging options ineffective, since this can facilitate seawater intrusion future upriver where sea level are high relative to land and river levels. An important distinction can be made between coastal inundation and coastal erosion in terms of the potential impacts on affected land and assets, including flood infrastructure, and the implications for acceptance, adaptation, mitigation, and/or modification options. That is, responding to inundation may focus on structure or building elevations and levels, whereas responses to erosion are more likely to involve retreat and/or shoreline protection.

Groundwater is the water that is present in soil pore spaces and/or in rock formations and fractures. Typically this water has an upper surface or saturation elevation located below the surface of the land – the groundwater table – but in low-lying coastal areas or where pressurised springs occur the groundwater table may meet the land surface and be accompanied by surface water ponding. Groundwater levels vary spatially as well as temporarily, with seasons, inter-annual climatic cycles, and with extreme meteorological events. These levels are of concern when examining flooding hazards and management options for several reasons. These include that the layer of land between the Earth's surface and the groundwater table represents potential rainfall infiltration and water storage space; the level of the groundwater table is a critical part of the design capacity of soakage components of any stormwater typology; and shallow groundwater tables are a key ingredient in liquefaction hazards.

Earthquakes represent the sudden release of stored elastic energy in the Earth's lithosphere, caused by its abrupt movement or fracturing along zones of pre-existing geological weakness, resulting in the generation of seismic waves (Smith and Petley 2009). Earthquakes induce ground It is challenging to predict the future likelihood of earthquake hazards across a catchment such as the Ōpāwaho Heathcote, besides mapping known fault lines that could affect the area (most of which are located outside the catchment), and historical uplift/ subsidence rates. In this report we examine three sets of recent earthquake data from the Canterbury Earthquake Sequence (CES) – peak ground acceleration, ground shaking intensities, and net vertical displacement – as well as relating the earthquake hazard to changes in liquefaction risk, mass movements and ground water elevations, all of which have implications for FPF hazards (Figures 1 and 2).

Mass Movement is an umbrella term that refers to the movement of rocks, soils and other materials through geomorphic processes such as rapid soil erosion, and mass movement via rock falls, landslides, ground slumping, slip/sheet and slope erosion, and tunnel gully erosion. In the Ōpāwaho Heathcote catchment, the hillside sub-catchments are particularly at risk of mass movements and soil erosion due to their steep elevations, loess rich soils prone to the development of impermeable subsurface layers and pipe failures, and due to the availability of elevated rock faces and materials.

3. Multi-hazard analysis approach

This report focusses on the potential effects on FPF flooding of the six key multi-hazards listed above. It does not examine in detail hazards that are unlikely to produce changes in the FPF hazard (e.g. drought, extreme temperatures, geomagnetic storms) in the Ōpāwaho Heathcote catchment (e.g. volcanic eruption or snow avalanche), nor does it examine certain low-probability hazards that might exhibit no spatial variation within the catchment (e.g. a meteorite impact).

At the moment there is no international standard approach to multi-hazard analysis, with analysis, vulnerability and risk methodologies varying between different natural hazards and research investigations (e.g. King and Bell 2005; Seville 2008; Smith and Petley 2009; Kappes *et al.* 2012; Gill and Malamud 2014; and Liu et al. 2016, to name but a few different approaches). Most approaches are, however, either spatially oriented or thematically defined (Kappes *et al.* 2012).

This project is primarily thematically defined, since it focuses on fluvial and pluvial flooding as its primary hazard and all other hazards are assessed with respect to their impact on flooding. However, we also analyse spatial patterns in multi-hazard interactions across the Ōpāwaho Heathcote Catchment in the form of maps and a breakdown of the combined set of hazards that affect each sub-catchment.

Multi-hazards is not a new concept, though its track record of application is still relatively nascent. A useful example framework for what constitutes a multi-hazard approach has been described by Gill and Malamud (2014), as illustrated in Figure 3. This approach involves four key steps that form a critical pathway for moving from a multi-layer 'single hazard' approach to a 'multi-hazard' approach. Steps 1 to 3 form the substantive basis of the Ōpāwaho Heathcote catchment analysis in this report.

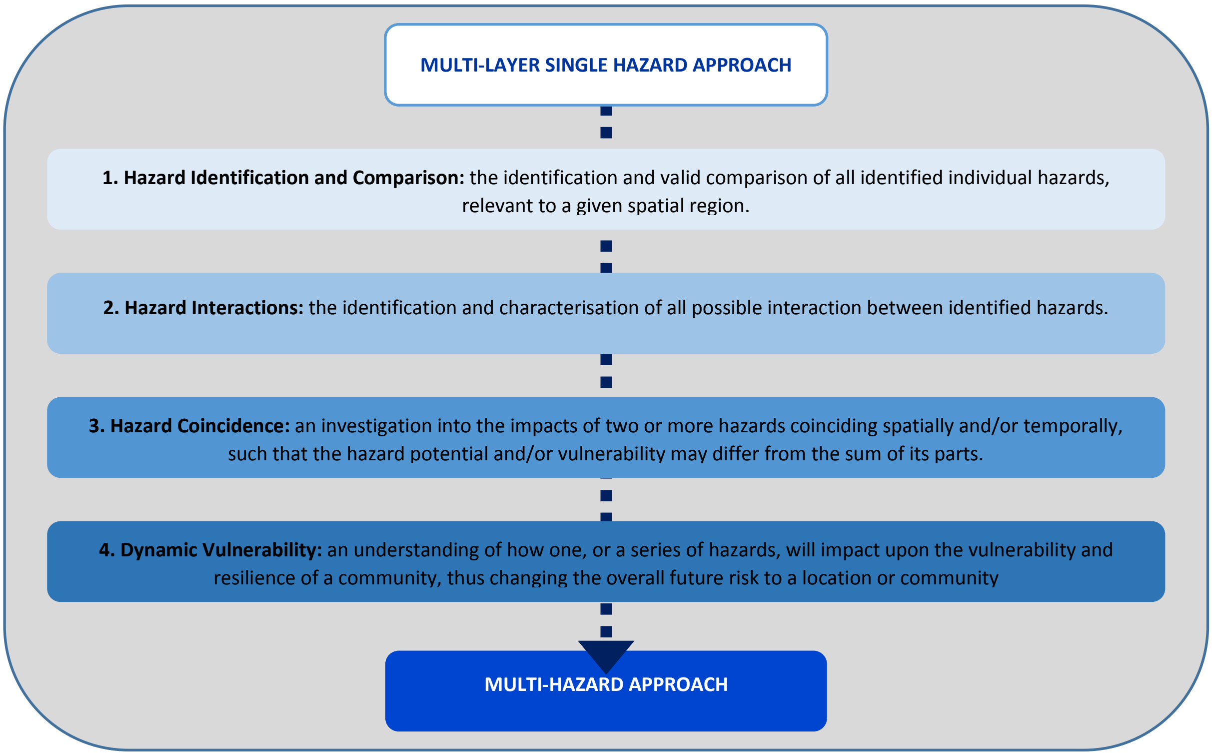

Figure 3. Framework for moving from a single hazard to a multi-hazard approach, including 4 key steps (modified from Gill and Malamud 2014, p718).

Step 1 - hazard identification and comparison - is relatively straight forward, using a spatially oriented methodology. However, difficulties arise in hazard comparisons since not only do different hazards have different natures, intensities, return periods and effects on the environment, but their intensities are also measured differently (Carpignano *et al.* 2009). Especially challenging is the non-uniform reference units (Kappes *et al.* 2012). This issue can be overcome to some extent by either using a standardising classification technique and/or the development of indices using a continuous or semi-quantitative approach (e.g. Menoni 2006).

Step 2 – hazard interactions - comprises the identification and characterisation of all possible interactions between the hazards identified in Step 1. It should be noted that in this report only interactions between the FPF hazard and each of our six key multi-hazards have been assessed (i.e. influences of the multi-hazards on FPF hazard have been assessed and not vice versa, and interactions between the six multi-hazards have not been assessed, in great detail), making it a selective and 'one-way' analysis.

Step 3 – hazard coincidence - indicates the need to investigate the impacts of the spatial and/or temporal coincidence of two or more hazards. This can be done qualitatively, based on a process focus (Hart 2016) or quantitatively as exemplified by Kappes *et al.* (2012). We have attempted both analysis options.

The outcome of the first three aspects of the multi-hazards approach illustrated in Figure 3 as applied in the present project was to identify, and understand the underlying reasons for, the parts of the Ōpāwaho Heathcote catchment that are most exposed to multi-hazards exacerbation of FPF hazard.

Step 4 – dynamic vulnerability – did not form a part of the present report. Rather it is anticipated that the information produced from Steps 1 to 3 will be used, alongside other kinds of data (e.g. social, cultural, economic and built environment data), in the latter stages of the wider FPF project to establish how a series of hazards might impact a community and that community's options for managing the FPF hazard.

4. Ōpāwaho Heathcote catchment multi-hazard analysis results

Below the results are presented of the Ōpāwaho Heathcote catchment application of Gill and Malamud's (2014) step by step approach for moving towards a multi-hazards analysis (Figure 3). Available information on the potential impact of each non-FPF multi-hazard was collated, including variation in their individual and combined influences across the catchment in the form of Maps 1 to 7, and information on the certainty of the multi-hazard information provided, with gaps in available information were highlighted in Appendix 1. Also in Appendix 1, results are discussed in terms of each non-FPF multi-hazard, and their associated key concepts for understanding interactions with, and its potential effects on, the Ōpāwaho Heathcote catchment fluvial and pluvial flood-scape.

4.1 Step 1 Hazard identification and comparison

Table 1 illustrates a quantitative approach to hazard identification and comparison for Ōpāwaho Heathcote catchment, applied to the six key multi-hazards plus the FPF hazard, based on international hazard intensity classifications (Kappes *et al.* 2012), as opposed to local scenario calibration. In international assessments, flooding, tsunami, and coastal inundation hazard intensity is typically quantified in terms of water depth whereas for coastal erosion, liquefaction, mass movement and soil erosion, hazard intensity is typically measured in terms of the percentage of land area that is affected versus stable. There are a plethora of measures for quantifying earthquakes hazard intensity, with Table 1 listing three commonly employed metrics of relevance to the multi-hazards assessment conducted in this project: peak ground acceleration (PGA), shaking intensity; and vertical ground displacement.

Maps 1 to 6 (along with their methodological explanations in Appendix 1) represent another, more spatially focussed way of identifying areas affected by the six key multi-hazards, using locally calibrated scenarios and data analyses.

It should be noted that the data used to produce these hazard maps represents several different timeframes. The maps indicating coastal erosion and coastal inundation risks represent future predictions, the maps indicating tsunami inundation indicate possible future events modelled across contemporary water and land levels (e.g. sea level rise effects have not been considered), while the map illustrating groundwater table depth below surface shows the current median water table situation, and the maps showing aspects of the earthquake hazard represent recent historical data (from the CES). The maps concerning liquefaction and mass movement hazards show both past event and future predicted risk data. As noted earlier, difficulties arise in hazard comparisons due to differing ways of characterising and quantifying the intensities and return periods of prediction timescales of each hazard. As such, Maps 1 to 6 should not be viewed as 'like for like' spatial pattern analyses. As an example, the coastal inundation risk areas (Map 3) are based on 50 and 100 year MSL rise projections while the tsunami inundation assessment (Map 1) used an 1:2500 year return period South American earthquake scenario.

Table 1. Hazard intensity classification matrix for the Ōpāwaho Heathcote catchment multi-hazards examined in this report (based on the classification of Menoni 2006; and Kappes *et al.* 2012 as opposed to local calibrations)

Natural Hazard	Intensity Scales			
	Low	Medium	High	Parameters
Fluvial/ Pluvial Flood	<0.25	0.25-1.25	>1.25	Flood Depth (m)
Tsunami Inundation (far field)	<0.25	0.25-1.25	>1.25	Inundation Depth (m)
Tsunami Inundation (regional)	<0.25	0.25-1.25	>1.25	Inundation Depth (m)
Coastal Erosion	<5	5-15	>15	Percentage of erosional surface vs. stable surface
Coastal Inundation	<0.25	0.25-1.25	>1.25	Inundation Depth (m)
Groundwater Level	>3	1-3	<1	Median water table depth below ground surface (m)
Earthquake - PGA	<10	10-30	>30	PGA, Peak Ground Acceleration (%g)
Earthquake - Shaking Intensity	<6	6-8	>8	Shaking Intensity http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/b0001igm/
Earthquake - Vertical Displacement	<0.3	0.3-0.9	>1	Vertical Displacement (m)
Liquefaction	<5	5-15	>15	Percentage of liquefaction surface vs. stable surface
Mass Movements	<5	5-15	>15	Percentage of mass movement surface vs. stable surface
Soil Erosion	<5	5-15	>15	Percentage of soil erosion surface vs. stable surface

Table 2. Matrix of example hazard interaction types and considerations relevant to flood infrastructure decisions. Colour key: light green indicates long-term and/ or low probability impacts, bright green indicates medium-term and/or intermediate probability impacts, while the darker green indicates near-term, likely impacts, grey indicates not significant or applicable for this project. FP stands for fluvial and/ pluvial flooding.

Hazard	Non-FP flood hazard occurrence information	FP flooding triggered?	FP flooding probability or consequences increased?	FP flooding probability or consequences decreased?	Spatial and temporal coincidence of FP flooding and other hazard?
Tsunami (Map 1)	1 in 2500 year return period		Severe spit erosion from an extreme tsunami would affect functioning of Ōpāwaho Heathcote rivermouth		Potentially severe consequence for coast-proximal and lower river reach infrastructure
Coastal erosion (Map 2)	50 and 100+ year future projections		Spit erosion under future sea levels could affect functioning of the Ōpāwaho Heathcote rivermouth		Flooding can enhance coastal erosion, in turn influencing the location, design & resilience of near-coast flood infrastructure
Coastal inundation (Map 3)	50 and 100+ year future projections		Both flooding & coastal inundation exacerbated when two hazards coincide with coastal inundation (e.g. extreme storms today and more commonly with future predicted sea level rise), affecting drainage network efficiency	Not expected according to current sea level rise projections	Flood levels enhanced by coastal inundation, undermining fluvial/pluvial flood design standards in coastal and lower catchment areas
Groundwater table (Map 4)		Rises in the groundwater table can induce surface flooding in low-lying, coastal & river proximal sub-catchments	Flooding thresholds lowered where groundwater rises, affecting design standards in areas with little free board	Occurs under sea level fall scenarios – not predicted under present sea level rise projections	Of concern regards design standards in areas with little free board
Earthquakes, including vertical displacement and liquefaction (Map 5)		Vertical land displacement and liquefaction changes to ground elevations & river channels can trigger tidal flooding	Vertical displacement and liquefaction can increase flooding in lowlying parts of the catchment	Uplift can decrease flooding in parts of the catchment	Significant exacerbation of FPF hazard possible via a myriad of stormwater and drainage network changes
Mass movement (MM), including soil erosion and mass movements (Map 6)		Landslides creating earth dams can trigger localised ponding & dam-break flash flooding – a possible issue in Ōpāwaho Heathcote Port Hill sub-catchments and tributaries	Intense rainfall can trigger MM, providing a sediment pulse: design flood infrastructure in areas adjacent to hillside sub-catchments for heavy sediment loads		Very likely temporal and spatial coincidences between flood and shallow earth process hazards, exacerbating FPF hazard

Table 3: Ōpāwaho Heathcote catchment hazard intensity matrix analysed to the sub-catchment level. Note: yellow = low risk, orange = medium risk, and red = high risk, as categorised in Table 1 (i.e. not based on local calibrations).

		Sub-catchment																										
Natural Hazard	**Timescale**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18a**	**18b**	**18c**	**18d**	**19a**	**19b1Aidan**	**19b1OldHals**	**19b2**	**20**	**21**	**22**
Flood	predicted																												
Far Field Tsunami Inundation	predicted																												
Regional Tsunami Inundation	predicted																												
Coastal Erosion	predicted																												
Coastal Inundation	predicted																												
Groundwater Level	contemporary model based on measurements																												
Earthquake PGA	historical measured																												
Earthquake Shaking Intensity (MMI)	historical measured																												
Earthquake Vertical Displacement *	historical measured	+																											
		-																											
Liquefaction	predicted & historical measured																												
Mass Movements	predicted																												
Soil Erosion	predicted																												

*where + refers to uplift and - refers to subsidence

4.2 Step 2 Hazard interactions

For this step we reviewed available literature and data to identify and characterise possible interactions between the FPF hazard and each of the six focus multi-hazards. We then classified the flooding multi-hazard interactions according to the four part classification system of Gill and Malamud (2014, p684).

A summary interaction assessment is presented in Table 2, which is effectively a matrix of key multi-hazard interaction types, with sample descriptions of process linkages and FPF hazard management consequences. Colours indicate the level of expected multi-hazard interactions in the Ōpāwaho Heathcote catchment, while columns indicate the direction of the resultant effects (i.e. triggered, increased or decreased FPF hazard) as well as the intensity of spatial and temporal hazard coincidence.

Appendix 1 provides more details of the available literature describing hazard interactions and the process linkages between multi-hazard phenomena as well as knowledge, data, and analysis limitations and gaps.

Of note, coastal inundation, earthquakes (including liquefaction and other effects), and mass movement exhibit the most extensive levels of multi-hazard interaction with FPF hazard. And all bar one of the analysed multi-hazard interactions (earthquakes), consistently produce increases in the FPF hazard. The implications of this analysis are that multi-hazard interactions generally enhance the FPF hazard in the Ōpāwaho Heathcote catchment, as opposed to triggering FPF hazards. Management plans which exclude adjustments for multi-hazard interactions are likely to underestimate the FPF hazard in numerous different ways.

4.3 Step 3 Hazard coincidence

In the case of this project, a qualitative assessment was the first step to address these aspects (see the colour coding in Table 2 and description above in section 4.2). Additionally, a quantitative approach was applied using the international hazard intensity classification methodology outlined in Table 1. This is the most frequently used approach to allow the comparison of different hazards, though there are many different classification methods. The hazard intensity classification matrix used in Table 1 is based on the simplified approach for assessing hazard intensities on a regional scale (>1:50,000) used by the *Applied Multi Risk Mapping of Natural Hazards for Impact Assessment (ARMONIA) Project* in Europe (Menoni 2006; Kappes et al. 2012). There is also a matrix for the local scale (i.e. less than 1:50,000, Menoni et al. 2006) but the parameters either had the same intensity scale or were not obtainable for our study area.

Table 3 illustrates the resultant Ōpāwaho Heathcote catchment hazard occurrences (past, present or future predicted) and intensities for each sub-catchment. It can be seen that the sub-catchments with the greatest number of high intensity multi-hazard risks are generally concentrated in the lower reaches of the catchment. Hazards which tend to be of greater risk to the lower catchment are fluvial/ pluvial flood, tsunami, coastal inundation, coastal erosion, shallow groundwater levels, liquefaction and earthquake vertical displacement (though the latter is easier to interpret via Map 5a due to the numerous small pockets of high intensity uplift and/or subsidence experienced in most catchments, even when the majority of certain sub-catchments only experienced low or medium uplift and/or subsidence).

Hill areas are at greatest risk for mass movements and soil erosion, though there is the potential for this risk to cascade to the lower sub-catchments such as when sedimentation clogs drainage systems and/or increases flooding risk via landslide dam collapse and flash flooding. Hazard risk in the upper plains reaches of the catchment (sub-catchments 13-15) are mostly concentrated around their eastern margins, with few high risk hazards affecting Hornby and Middleton areas and further inland.

Map 7a represents the multi-hazard overlay on the catchment and Map 7b shows the individual sub-catchments with a catalogue of their associated multi-hazard exposures. It should be emphasized that these are only the hazards that have been directly recorded or modelled as impacting these sub-catchments. There has been no attempt to map any secondary or tertiary flooding hazards, which may occur as a result of these hazards, such as the multi-hazard cascade examples given in Table 2.

5. Rainfall and storm analysis gap

The effect of rainfall and storms on the Ōpāwaho Heathcote catchment has not been directly addressed in this multi-hazard analysis, with flooding projections based on a generic 2-step rainfall intensity gradient as recommended in the Christchurch City Council (CCC) Waterways, Wetland and Drainage Guide (CCC 2011), with the higher intensity occurring over the Port Hills (Figure 1). As part of the forecasting to minimise risk part of flooding solutions, we recommend that it would be beneficial to have an idea of the synoptic weather conditions in which flooding is most likely to occur in the Ōpāwaho Heathcote catchment. The following provides some context on rainfall and storm phenomena for the present multi-hazard analysis.

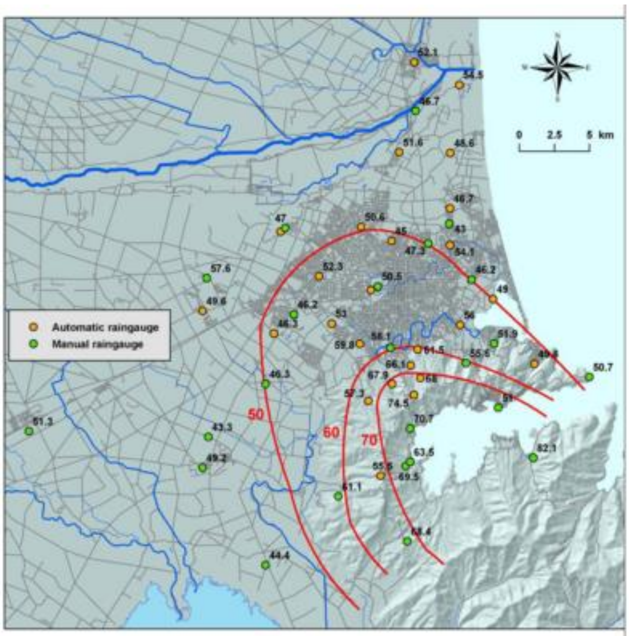

Figure 2. Median annual maximum 24-hr rainfall (mm) and isolines (mm): note the isoline generating process excluded Lyttelton gauge totals due to poor data reliability (Griffiths et al. 2009).

Across coastal areas of Canterbury including the Ōpāwaho Heathcote catchment margins, zonal airflows (i.e. those with a westerly wind component) generally produce little in the way of rainfall. That is, it is also unusual for high pressure synoptic weather to produce convective storms in the region (unlike, for example, the central North Island). Rather, heavy rainfall results primarily from trough or low pressure synoptic situations (Macara 2016). Low pressure systems centred to the south or southeast of the South Island with a south-westerly airflow over the region are most likely to produce the high-intensity short duration rainfall associated with a thunderstorm or frontal rain band (Griffiths et al. 2009; Renwick 2011; Kidson 1994).

The second synoptic weather type to produce rainfall over Christchurch is an easterly quarter airflow, with low pressure centred to the north-east of the South Island. These situations are more likely to produce lower intensity, long duration rainfall events. Rainfall distribution studies show a general northwest-southeast rainfall intensity gradient across Christchurch as a whole (Macara 2016; Griffiths et al. 2009).

6. Conclusion

This report has outlined the current state of knowledge (including gaps) and data available on the multi-hazards interactions that might affect fluvial and pluvial flooding hazard in the Ōpāwaho Heathcote catchment. Although only a one-way analysis of the potential effects of selected multi-hazards *on* FPF hazard, our review highlights that the Ōpāwaho Heathcote catchment is an inherently multi-hazard prone environment. The implications of the interactions and process linkages revealed in this report are that several significant multi-hazard phenomena must be taken into account in order to design a resilient FPF hazard management strategy for the Ōpāwaho Heathcote catchment.

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Appendix 1 Multi-hazards analyses for the Ōpāwaho Heathcote Catchment: methods, results and literature resources

See Appendix 2 for details of data sources and layers used to construct each map.

Map 1: Tsunami Inundation (LDRP110_MH1)

While modern tide gauge records indicate that small tsunamis are very common around most open-ocean shores, large tsunamis are believed to be low-probability but high-impact events in the Christchurch area. The return intervals for large tsunamis are much longer than most FPF scenario or planning timeframes. Further, large tsunami probability figures are typically estimated based on limited paleo data, such as one or two deposit layers in one or two stratigraphic cores per bay or sub-region (e.g. in southern Pegasus Bay). Thus we may have limited confidence in detailed statistical analyses of the probability of occurrence of future large tsunamis but, when they occur, such events have the potential to impact extensive coastal, low-lying plain and lower river reach areas.

For the Ōpāwaho Heathcote catchment, the most researched tsunami risk comes from distant source waves emanating from large earthquakes in South America (Berryman 2005; Lane *et al.* 2014). Regional source tsunami scenarios from other Pacific locations have also been modelled (e.g. Kohout *et al.* 2015), with the predicted inundation extents less than those from the worst case South American scenario (e.g. Lane *et al.* 2014). In addition, there is a risk from local source tsunami: Pegasus Bay offshore fault lines have been mapped (Barnes 2012), but the potential tsunami hazard posed by these local features has yet to be quantified.

Both Lane et al. (2014) and Kohout et al. (2015) modelled tsunami inundation using RiCOM. Lane et al. (2014) looked at the potential impact of a far field tsunami on the Canterbury coast, using a moment magnitude 9.485 earthquake originating in the subduction zone off Peru/Chile across the Pacific Ocean, assuming the largest surge arrives at high tide. This is a 1-in-2500 year 'worst-case scenario' tsunami, and has been used for evacuation and emergency management planning rather than as a standard for landuse planning (which usually uses shorter return period events of up to 1-in-500 years).

Kohout et al. (2015) looked at the impact of two regional source tsunamis - one originating from Hikurangi Subduction Zone, generated by a moment magnitude 9.0 earthquake and assuming the largest surge arrives at high tide. The second tsunami originating from Wairarapa Fault, generated by a moment magnitude 8.6 earthquake and assuming the largest surge arrives at high tide. While these events arrived much quicker than the distant source tsunami, modelling indicates that the worst-case scenario tsunami inundation is less than that of a far field tsunami.

Map 1a illustrates Lane et al.'s (2014) 'worst case' tsunami scenario while Map 1b illustrates Kohout et al.'s regional source tsunami scenario. Under these scenario waves would travel across the Pacific Ocean into Pegasus Bay and then the Avon-Heathcote Estuary Ihutai, to reach the mouth and lower reaches of the Ōpāwaho Heathcote River, potentially eroding shorelines (Lane *et al.* 2014) and temporarily blocking fluvial drainage. The potential for such events is of interest to this project since any flooding infrastructure or management actions implemented in the area of tsunami inundation would ideally be resilient to tsunami-induced inundation and erosion (Table 1). According to the modelled results illustrated in Map 1, this would include inundation in sub-catchments 1 to 5.

It is worth noting that the modelled results illustrated in Map 1 are a first estimate and do not, for example, include consideration of future changes in sea levels, shorelines and land levels. Research from elsewhere indicates that topography and other factors matter when it comes to the impacts of large tsunami. Of relevance in the Ōpāwaho Heathcote setting, large tsunami waves can travel many kilometres up rivers and other inundation 'conduits'such as drainage canals and stormwater systems (Kain *et al.* 2013, 2014). For example, in the 2011 East Japan tsunami event, waves travelled 1 to 3 km overland across the Tohoku plain versus up to 6 km upstream in river channels, and tsunami waters were observed 'exploding' up stormwater pipe networks. The earthquake that triggered this tsunami also pre-lowered the coastal land elevations and defence systems, leading to more extensive and severe coastal inundation. While the Ōpāwaho Heathcote catchment has no tsunami defences equivalent to those in Tohoku in 2011, changes in elevation of stopbanks and FPF defences are worth considering for near-field tsunami scenarios. The Ōpāwaho Heathcote rivermouth is somewhat sheltered by the presence of New Brighton Spit, but this feature is predicted to undergo significant erosion from the initial waves of a large tsunami event (Map 1) such that less protection of the Ōpāwaho Heathcote catchment may be expected from the spit during subsequent waves in any large event. This means that the spatial inundation extent illustrated in Map 1 may underestimate the potential for effects in riverside sub-catchments during particularly large tsunami events. Also of significance when considering different FPF management structures, it is important to be mindful that certain types of flood structures can 'trap' inundating water coming from ocean directions, leading to extended flooding and salinization (see affected sub-catchments listed in Table 3).

Other tsunami inundation modelling studies which have been assessed but not included in the multi-hazard analysis represented in Map 1 are:

- Gillibrand et al. (2011), who present tsunami modelling across Canterbury but do not include Christchurch modelling as that is published in Lane et al. (2014) and Kohout et al. (2015).
- Hart and Knight (2009), who utilised pre-earthquake LIDAR data and their inundation model study area of New Brighton Spit, and Griffiths (2005) who applied a bathtub modelling technique to examine potential tsunami inundations in and around the Avon-Heathcote Estuary Ihutai.

Related studies include Berryman (2005), Power (2013) and Gill et al. (2015) who review New Zealand's tsunami hazard, risk and public policy but do not go into sufficient detail for the purpose of this study. Horspool et al. (2015) quantified the local tsunami risk posed by a 9.0 Hikurangi Subduction Zone tsunami to people and built structures. In their report to the Ministry of Civil Defence and Emergency Management, they estimated that 5.8 m waves would impact Christchurch, arriving one to two hours after the earthquake, with a modelled 3010 deaths, 2598 injuries, $4,273 million economic loss. Their report focused on modelling tsunami risk and impact, although no spatial inundation material was presented.

A wide variety of international literature has been published on tsunami hazards, especially subsequent to the 2005 Indian Ocean tsunami. One area of potential interest to this project is recent research on the interaction between tsunami inundation, tides and river flow, with Kalmbacher and Hill (2014) noting that the tidal flow had a much greater effect on tsunami inundation than river flow. Tolkova et al. (2015) takes this further, highlighting two important features for tsunami-fluvial interactions. Firstly tsunamis are able to move greater distances up rivers than over land. Secondly, tsunami inundation was affected by tides, with an attenuation of tsunami during receding tides noticed in the Columbia River (USA) estuary (Tolkova, 2013). This could be significant in the Ōpāwaho

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Map 2: Coastal Erosion (LDRP110_MH2)

Several studies have examined a range of historical and future shoreline and/or sediment budget trends for the coast of wider Pegasus Bay (Campbell 1974), and Christchurch city (Kirk 1979; Hicks 1998; Duns 1995; Tonkin and Taylor 1999, 2013, 2015), while other studies have investigated sediment dynamics and shoreline trends within the Avon-Heathcote Estuary Ihutai (Macpherson 1978; Findlay and Kirk 1988; Hicks 1993; Burge 2007; Jupp 2007). At the time of publication of this report, the most relevant information concerning the future predicted coastal erosion hazard along the estuary margins of the Ōpāwaho Heathcote catchment was the *Coastal Hazard Assessment: Stage 2* report by Tonkin and Taylor (2015).

Tonkin and Taylor (2015) identified areas susceptible to coastal erosion, which they termed Coastal Erosion Hazard Zones (CEHZ) for open coast and sheltered or 'harbour' environments (the latter including the Avon-Heathcote Estuary Ihutai). For both the open and 'harbour' coast (including the estuary), a building block approach was taken, including evaluation of short-term storm, dune stability, long-term shoreline, sediment budget, and future-predicted Bruun Rule type sea level rise response factors. A shoreline translation method was also applied to the harbour coasts. CEHZ zones were mapped for both 2065 'likely' (66%) and 2115 'potential' (5%) scenarios, using actual and extrapolated Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 8.5 sea level rise projections.

The results of the Tonkin and Taylor (2015) assessment are represented in Map 2, with sub-catchments 1 to 3 predicted to be potentially affected by coastal erosion by the timescale of 2065 and sub-catchments 1-6 predicted to be potentially affected by coastal erosion by the time scale of 2115. While the estuary shoreline results illustrated in Map 2 are of direct relevance to this multi-hazard analysis in terms of their spatial overlap with the catchment and its flood zones, the open coast results should not be ignored since any significant changes in the New Brighton Spit open coast would affect erosion rates and exposure of the landward estuary margins, including the shorelines of the Ōpāwaho Heathcote catchment. One implication of these findings is that any FPF flooding infrastructure or management activities planned for the future potentially affected sub-catchments needs to recognise the potential for coastal erosion and to have a planned response to the potential shoreline translation. Another implication is that the effects on the coastal sediment budget should be considered when evaluating any significant dredging operations or structures that limit the discharge of sediment from rivers to the coastal zone.

Note: Map 2 will need adjustment when (i) Tonkin and Taylor complete their coastal hazards revisions (due for completion in mid-2017) in response to peer review panel recommendations and a new Ministry for the Environment guidance manual on coastal hazards and climate change (due to be published in early 2017 – see Bell et al.), and (ii) after the Christchurch City Council completes subsequent adaptive management, consultation and planning stages of the assessment (timeframe unknown). In addition, a new Environment Canterbury (ECAN) coastal monitoring report for Pegasus

Bay will likely be commissioned for 2017/18, which may provide additional useful information for quantifying future coastal erosion hazards.

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Map 3: Coastal Inundation (LDRP110_MH3)

Several studies have examined past and future predicted coastal inundation hazards within the Avon-Heathcote estuary Ihutai (Lamb 1997; Tonkin and Taylor 1999, 2013, 2015; CCC 2014; Allen et al. 2014), while other broadly relevant studies have investigated storm surges along the east coast of New Zealand (Heath 1979; Bell et al. 2000; Thiebaut et al. 2009; Goring 1995; Goring et al. 2011).

At the time of publication of this report, the most relevant information concerning the future predicted coastal inundation hazard along the estuary margins of the Ōpāwaho Heathcote catchment was the *Coastal Hazard Assessment: Stage 2* report by Tonkin and Taylor (2015). This report identified areas susceptible to coastal inundation, which they termed Coastal Inundation Hazard Zones (CIHZ), for open coast and sheltered or ‘harbour’ environments, the latter category including the Avon-Heathcote Estuary Ihutai. CIHZ zones were mapped for both 2065 ‘likely’ (66%) and 2115 ‘potential’ (5%) scenarios, using actual and extrapolated Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 8.5 sea level rise projections.

The Avon-Heathcote Estuary Ihutai CIHZ was modelled using a TUFLOW software method, which simulated the physics of the tides and sea levels to dynamically map inundation levels based on LiDAR derived post-earthquake topography and detailed estuary bed bathymetry survey data. This TUFLOW modelling did not include river base flows, or the effects of coincident rainfall, the inclusion of which might have increased the extent of predicted inundation. Worst case wind and wave set up were used in the modelling since no in-depth analysis of the occurrence of extreme wind and wave set up and storm surges is presently available for the Canterbury coast. This would be a useful future investigation to complete, particularly if it were to include correlation analyses of the relationships between storm surge in and outside of the Avon-Heathcote Estuary Ihutai and Ōpāwaho Heathcote River catchment flooding.

Map 3 illustrates areas predicted by Tonkin and Taylor (2015) to be affected by coastal inundation hazards by the timescales of 2065 and 2115, with sub-catchments 1 to 8 affected by 2065 and inundation affecting a greater area of these same sub-catchments by 2115. Of significance for the Ōpāwaho Heathcote catchment, low-lying areas of the catchment and river channel that discharge into the estuary are highly vulnerable to coastal inundation since elevated ocean and estuarine water levels can block the drainage of inland systems, thereby compounding any FPF hazard event. Coastal inundation can also overwhelm stormwater and other drainage network components, meaning that their design capacity should consider the effects of coastal inundation.

An important distinction should be made between coastal inundation and coastal erosion in terms of the potential impacts on affected land and assets, including flood infrastructure, and the implications for acceptance, adaptation, mitigation, and/or modification options. That is, responding to inundation may focus on structure or building elevations and levels, since unlike erosion, inundation does not necessarily mean the loss of land.

Note: Map 3 will need adjustment when (i) Tonkin and Taylor complete their coastal hazards revisions (due for completion in mid-2017) in response to peer review panel recommendations and new Ministry for the Environment guidance manual on coastal hazards and climate change (due for publication in early 2017), and (ii) after the Christchurch City Council completes subsequent adaptive management, consultation and planning stages of the assessment (timeframe unknown).

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Map 4: Groundwater Inundation (LDRP110_MH4)

Groundwater is the water that is present in soil pore spaces and/or in rock formations and fractures. Typically this water has an upper surface or saturation elevation located below the surface of the land – the groundwater table – but in low-lying coastal areas or where pressurised springs occur, the groundwater table may meet the land surface and be accompanied by surface water ponding. Groundwater levels vary spatially as well as temporally, with seasons, inter-annual climate variability and with extreme meteorological events. These levels are a major concern when examining flooding hazards and management options for several reasons. These include that the layer of land between the Earth's surface and the groundwater table represents potential rainfall infiltration and water storage space (sometimes termed 'freeboard'); plus the level of the groundwater table is a critical part of the design capacity of soakage components of any stormwater typology; and shallow groundwater tables are a key ingredient in liquefaction hazards, with their cascading effects of land elevations, river channel capacities, and stormwater and surface infrastructure such as stopbanks.

The effect of urbanisation on shallow groundwater is complex and has varying degrees of influence depending upon the hydrogeological setting and stormwater management practices (Barron et al. 2013). In shallow water table environments, the permeability of the subsoil is a critical factor in how the water travels. An increase in runoff in a semi-permeable ground environment does not necessarily mean and increase in the overland runoff, with Barron et al. (2012) finding that the majority of the additional runoff actually caused a greater increase in subsurface flows compared to overland. However, less permeable soils led to an increase in surface runoff. In the Ōpāwaho Heathcote catchment, increases in subsurface runoff are a particular hazard for the loess covered hill slopes as this can trigger mass movements, as mentioned below under Map 6.

Post-earthquake measured median groundwater depth below surface is been presented in Map 4. This was calculated using monitored data from Sept 2010 to Nov 2013 (van Ballegooy 2014). It should be noted that these are median levels, meaning that actual levels may be higher or lower at any particular time depending on hydrological conditions, with levels more likely to be higher in conjunction with flood events and wetter seasons. Much of the Canterbury Plains part of the Ōpāwaho Heathcote catchment has a water table <1m from the surface, though the water table rapidly descends to >6m below the surface in the upper Plains part of the catchment (sub-catchments 13 to 15). Parts of Waltham/Linwood (sub-catchments 5 & 6) and Spreydon (sub-catchment 10) have extensive areas with a particularly high water table, as do sub-catchments 18, 19 and 20 south of the river.

In all of the sub-catchments where groundwater depth below surface is shallow, it is necessary to be mindful not only of the reduced infiltration capacity or 'freeboard', but also of the cascading effect of this high water table in producing a liquefaction hazard during earthquake events, and thus the potential for earthquake-induced drainage network and stormwater infrastructure damage (refer to the section below for Map 5 for more details). In turn, subsidence induced by liquefaction and other earthquake processes during the CES directly affected groundwater depth below surface across large parts of the central Ōpāwaho Heathcote catchment (Hart et al. 2015), revealing that the design standards of key built environment components that relate to groundwater depth, such soakage feature capacities and ground strengths (which in turn affect river channel capacities and stop bank stability) are not resilient to earthquakes. In response to these lessons, it is perhaps worth exploring if blue-green infrastructure (e.g. employed in Portland, Oregon) would be more resilient in this multi-hazard environment compared to traditional stormwater designs.

The estuary margin subset of the Ōpāwaho Heathcote sub-catchments that currently have shallow groundwater depths below surface also face increasing future issues since sea level rise has the potential to elevate groundwater levels further in these areas, thereby compounding the liquefaction and other earthquake associated multi-hazard cascades (Hart et al. 2015; Quilter et al. 2015).

A Note on Earthquake-Induced Groundwater Fluctuations

A comparison of pre and post-earthquake groundwater elevations (i.e. absolute groundwater levels as opposed to their depths below surface) indicates that the near-surface water table elevation across Christchurch was, for the most part, unaffected by the earthquake sequence (van Ballegooy et al. 2014). While there were a few anomalies reported, it was unclear whether these were earthquake-induced or merely the result of natural groundwater fluctuations (van Ballegooy et al. 2014). Further afield, Cox et al. (2012) reported some earthquake-induced changes in deeper groundwater aquifers across the central Canterbury Plains, though this is not expected to affect the Ōpāwaho Heathcote Catchment.

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Map 5: Earthquakes (LDRP110_MH5a & b)

Three classes of earthquakes have been identified as potential major hazards to the Christchurch area (Brackley 2012):

1. close proximity (Christchurch), moderate size (Mw 5.0-6.5);
2. regional (Canterbury Plains and Southern Alp foothills), large size (Mw 7.0-7.5); and
3. distant (Southern Alps), great size (around Mw 8.0).

It is currently impossible to predict exactly when, where and how future earthquakes will affect the Ōpāwaho Heathcote catchment. Despite these uncertainties, we do have an opportunity to conduct a retrogressive assessment of catchment area susceptibility to earthquake-related hazards based on data from the events listed in Table A1-1, while also acknowledging that the Ōpāwaho Heathcote catchment might not behave in exactly the same manner during future events. The 22nd February 2011 event, in particular, represented a severe event for the Ōpāwaho Heathcote catchment, so might reasonably be used as an 'extreme' if not 'worst case' scenario for the purposes of this multi-hazards analysis.

Table A1-1. Canterbury Earthquakes Summary

Earthquake Event	Type	Mw	PGA (m/s/s)	PGA (%g)	Reference
Darfield 4 September 2010	regional	7.1	0.12-0.5	0.4-12.8	Bradley & Hughes 2012
Christchurch 22 February 2011	close proximity	6.2	0.14-1.26	1.2-5	Bradley & Hughes 2012
Kaikoura 14 November 2016	distant	7.8	<0.1	1	Geonet (2016, November 21)
Hope Fault (modelled)	regional	7.1	0.6	6.1	Holden 2014
Alpine Fault (modelled)	distant	8.2	0.78 0.6	8 6.1	Holden 2014 McVerry 2006

There have been a number of studies focusing on various aspects of recent earthquake hazards and impacts in Christchurch, especially following the damaging CES, which included the 7.2 Mw Darfield earthquake on 4th September 2010, and the 6.4 Mw Christchurch earthquake on 22nd February 2011 (e.g. McClure et al. 2014; Alexander 2012). Earthquake-related effects identified as having the potential to impact on flooding in the Ōpāwaho Heathcote catchment include tsunami (discussed in the first part of this Appendix); vertical ground displacement (e.g. Measures et al. 2011; Beavan et al 2012; LINZ 2015); liquefaction (e.g. Brackley 2012; van Ballegooy et al. 2014; Santucci et al 2013; Quigley et al. 2013; Measures et al. 2011; Cubrinovski et al. 2011, 2012; Environment Canterbury 2011; Quilter et al. 2015) and mass movement (e.g. Heron et al. 2014; Khajavi et al. 2012). Several studies have also focused on the impact of the earthquakes on flooding (e.g. Allen et al. 2014; Tonkin & Taylor 2014; Cavalieri et al. 2015; Cox et al. 2012; Gillooly and Whyte 2012; Hart et al. 2015; Hughes et al. 2015)

The 2010-11 earthquakes affecting Christchurch were unusual in their very strong shaking relative to the size of the earthquake (Brackley 2012). Ground shaking was severe in both the Christchurch and Darfield events (Table A1-1), with vertical land movement in excess of 0.5-1 m occurring in parts of the Ōpāwaho Heathcote Catchment. In addition, shaking during these two events resulted in widespread liquefaction in the Canterbury Plains part of the Ōpāwaho Heathcote catchment, especially towards the east (Environment Canterbury, 2011; Measures et al. 2011; Brackley 2012; Cubrinovski et al. 2011, 2012). In comparison, the distant Kaikoura Earthquake of 14 November 2016 only resulted in a horizontal displacement of 0.02cm and little vertical displacement (Geonet 2016, November 18), and no observed liquefaction.

Relationships between earthquakes and flooding have been analysed in several reports subsequent to the Christchurch earthquakes (e.g. Allen et al. 2014, Tonkin & Taylor 2014; Cavalieri et al. 2015; Hart et al. 2015; Hughes et al. 2015), where analysis of vertical ground displacement showed that the upper parts of the Ōpāwaho Heathcote catchment have been subjected to tectonic subsidence as a result of the earthquakes, but the lower sub-catchments uplifted. This has had the effect of reducing river gradients (Hughes et al. 2012). These earthquake-induced land changes are considered to have substantially significantly increased the city's flood risk (Hughes et al. 2015), with the main factors contributing to the increased flood risk being the widespread tectonic and liquefaction-induced subsidence, alteration of water courses and the influx of sediment load to water courses. In addition, lowering of surface elevations relative to water tables is likely to have increased the liquefaction and flood hazard (van Ballegooy et al. 2014; Hughes et al. 2015; Quilter et al. 2015). The influence of groundwater levels on flooding has been discussed in more detail earlier in this appendix, with vertical ground displacement and liquefaction being the focus of in this section.

Historical earthquake vertical ground displacement (combined tectonic and liquefaction induced displacement) and liquefaction maps are presented in Maps 5a (vertical ground displacement) and 5b (liquefaction).

Vertical Ground Displacement

Vertical elevation changes from pre-earthquake to 13th June 2011 are represented in Map 5a and are based on vertical ground surface movement data (Beavan et al. 2012), obtained from the Geotechnical Database. All sub-catchments recorded vertical movement. However, there was a general uplifting around sub-catchments 1, 2, 3, 4, southern parts of 5 and 6, and the Port Hill parts of sub-catchments 7, 9, 11, 16, 17 and 21. This significantly altered areas along the bottom of the Port Hills and in a northeast line close to Ensors Road, with land generally subsiding to the west of this line (sub-catchments 5, 6, 8, 10, 12, 13, and 18). Beyond these sub-catchments (14 and 15), vertical ground displacement appears to have been more sporadic, with little widespread vertical movement in most remaining sub-catchments but some pockets of severe (>1m) uplift and subsidence.

Liquefaction

The results of Brackley's (2012) review of liquefaction hazard information (post the 4th September 2010 and 22nd February 2011 earthquakes) are represented in Map 5b, with flat areas within all sub-catchments affected during these events. The sub-catchments may be divided into three subsets based on the combination of topographic and liquefaction susceptibility criteria:

a. sub-catchments comprised wholly of plains topography, with widespread, extensive areas of historic and predicted liquefaction susceptibility (sub-catchments 3, 5, 6, 8, 10, 12, 18, 19, and 20);
b. sub-catchments comprised wholly of plains topography in the inland reaches of the catchment, with both unaffected areas and areas deemed liquefaction susceptible due to historic and predicted data (sub-catchments 13, 14 and 15); and
c. those comprised of both unaffected hill areas and plains areas that are predicted to be, or have been, significantly affected by liquefaction (sub-catchments 1, 2, 4, 7, 9, 11, 16, 17, 21 and 22).

Effects on FPF hazard

The earthquake associated risks of vertical ground displacement and liquefaction susceptibility have historically affected, or are in future predicted to affect, all of the sub-catchments of the Ōpāwaho Heathcote River. During the CES, these phenomena induced very significant changes in the drainage systems, including:

- extensive vertical displacement and liquefaction induced damage to stormwater greyware (pipes, inlet, outlets, grates/sumps, paved roads, curbs and channels), which collectively reduced functionality of the stormwater system;
- damage to the wastewater system, including cracked pipes, which helped to temporarily lower groundwater levels and increase stormwater drainage via the wastewater network on the one hand but which created a very significant pollution multi-hazard for FPF hazard on the other hand;
- liquefaction induced horizontal rafting of river banks, uplift and sedimentation of river channel beds, and vertical displacement induced river gradient changes - processes which collectively affected river drainage capacities;
- subsidence induced loss of soakage and infiltration capacities affecting detention and soakage basins, wetlands and vegetated swales and other unsealed earth surfaces;
- vertical displacement induced changes in the drainage conductivity of the topography, with increased basinisation in mid-catchment areas and uplift hindering drainage to coastal environments in the lower catchment;
- estuary subsidence (mainly around the Ōtākaro Avon catchment margins), increasing both FPF and coastal inundation flood hazards in coastal catchment reaches;
- estuary bed uplift (severe around the Ōpāwaho Heathcote margins, and partial around sections of the Ōtākaro Avon catchment margins), reducing tidal prisms and increasing bed friction, thereby producing an overall reduction the waterbody’s capacity to efficiently flush catchment floodwaters out to sea; and
- vertical displacement and liquefaction induced loss of/ changes to estuarine and riverine ecosystems (Allen et al. 2014; Hart et al. 2015).

All of these possible effects, both direct and cascading, need to be considered when evaluating the present and future capacities of the Ōpāwaho Heathcote catchment FPF flood management systems. These phenomena are particularly of concern for catchments like the Ōpāwaho Heathcote, in which stormwater networks cannot be built according to an idealised grid based form with plenty of inbuilt redundancy but rather which has to be constructed around the constraints imposed by stream and river channels (past and present), estuarine shorelines and complex hill topography.

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Map 6: Mass Movements (LDRP110_MH6)

For the purposes of this study, mass movement hazards are defined as "*the downslope displacement of surface material (predominantly soil and rock) under gravitational forces*" (Gill and Malamud 2014). Individual mass movement hazards considered include rockfall, slip/sheet and slope erosion, with the 'soil erosion' layer representing tunnel gully erosion. In addition, rockfall and landslides associated with earthquakes are also considered.

Causes and triggers of mass movements are often differentiated in landslide research, with causes referring to factors which make a slope susceptible to mass movements, and triggers being events which initiate the final failure (Smith and Petley 2009). Causes include weathering; increase in slope angle; removal of lateral support (often as a result of river erosion at its base); head loading (when additional weight is placed on a slope); changes in the water table; and removal of vegetation. Key triggers are loss of shear resistance as a result of increased moisture, usually as a result of intense or persistent rainfall; earthquake shaking and human activity (such as quarrying or slope cutting in road construction) (Smith and Petley 2009). Multi-hazard analysis is crucial in this context, where one hazard (e.g. earthquakes or severe storms) may trigger a secondary hazard (e.g. rockfall or tunnel gullying), and potentially also a tertiary hazard (e.g. a landslide blocking a river or excess sediment loads washing into drainage and flood management infrastructure, creating or exacerbating flooding and/ or impacting stormwater system functionality). A statistical analysis of the correlation between extreme rainfall events triggering mass movement versus FPF flooding represents a gap in the present literature.

A type of erosion common in the Port Hills is tunnel gullying, where water migrates down through loess sediment until it reaches a less permeable layer, concentrating to form and underground water channel. The progressive widening of such features eventually leads to their collapse (Basher 2013). Since this type of mass movement is triggered by groundwater flows, events are not necessarily coincident with extreme rainfall events (Ian Lynn, Soil scientist, Landcare Research, *pers. comm.* 2017). Tunnel gullying can cause a secondary flooding hazard by sedimentation of water courses, a phenomenon observed in the Ōpāwaho Heathcote River catchment (Hicks 1993; Perez 2012).

High erosion and high soil erosion risk areas have been presented in Map 6b, where soil erosion risk areas are representative of those areas at high risk of tunnel gullying, as identified by Environment Canterbury, and erosion risk areas represent areas which have been assessed as “being prone to an erosive process” by the Christchurch City Council. While exceptions occur, not unsurprisingly mass movement is primarily a risk to the Port Hills areas of the Ōpāwaho Heathcote catchment (sub-catchments 1, 2, 7, 9, 11, 16, 21), though there are one or two small but susceptible areas on the banks of the Ōpāwaho Heathcote River.

Historical mass movement events obtained from the Christchurch City Council have also been mapped (Map 6a) and it is worth noting that there are significant anomalies when comparing these areas with the risk map (Map 6b), highlighting the limitations of this particular hazard risk analysis. For example, the larger scale slip sheet mass movement appears to have historically occurred in sub-catchments 2 and 7. However, this does not preclude it occurring in any of the other risk areas, with the fact that there has been no recent event in some susceptible areas meaning that they could be even more susceptible.

Earthquake-Induced Mass Movements

Mass movements in the form of rockfalls and debris flows occurred on the Port Hills during the CES, resulting in building damage, fatalities and evacuations. These have been extensively mapped and analysed (e.g. Khajavi et al. 2012; Massey et al. 2013; Heron et al. 2014; LINZ 2015), highlighting areas prone to rockfall and at risk of cliff collapse. Evidence was also found of earthquake-triggered tunnel gully collapse in all Port Hills valleys (Stephen-Brownie 2012). Follow-on effects of these mass movements are likely to occur in major future events, with the possibility that earthquake-triggered mass movements could affect tributaries in the Port Hills sub-catchments areas. With rockfalls and slip/sheet mass movement a known hazard for parts of the Port Hills, there is also the possibility of an earth/ rock dam and subsequent upstream ponding.

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Appendix 2 Multi-hazards map details

All Maps

Coordinate System:

NZGD 2000 New Zealand Transverse Mercator

Base Map Layer(s):

1

Layer:	Canvas/Light Light Grey Canvas Basemap of New Zealand
Layer file source:	ESRI Basemaps
Credit(s):	Eagle Technology, Land Information New Zealand

2

Layer:	CHCHhillshade raster produced from the 2012 NZ 8m DEM using a hillshade transformation
Layer file source:	New Zealand 8m DEM (2012)
Credit(s):	Geographx, LINZ Data Service

Reference ArcGIS .shp files:

Layer:	Heathcote_HydrologicalCatchments.shp shape file of Heathcote hydrological sub-catchments
Layer file source:	Jacobs
Credit(s):	unknown

Layer:	CCC_Watercourse.shp shape file of CCC watercourses amended to show only Heathcote River and Cashmere Stream centre lines
Layer file source:	Jacobs
Credit(s):	CCC

Map 1: Tsunami Inundation Risk Map (LDRP110_MH1)

A combined distant and regional source tsunami inundation risk map.

Distant Source Tsunami:

This layer maps coastal inundation modelling from a distant source tsunami, produced by a moment magnitude 9.485 earthquake originating in the subduction zone off Peru/Chile across the Pacific Ocean, assuming the largest surge arrives at high tide. This is a 1-in-2500 year “worst-case scenario” tsunami, and has been used for evacuation and emergency management planning rather than as a standard for landuse planning (which usually uses shorter return period events of up to 1-in-500 years). Previous modelling was completed using a smaller magnitude 1868 South American tsunami event (Lane et al. 2012)

Modelling software used: RiCOM.

Model Limitations:

- Lower resolution bathymetry data in places introduces uncertainty errors.
- Assumed fixed bathymetry / topography - coastal erosion by early tsunamis waves could increase inundation by subsequent tsunamis waves.
- Rivers were not explicitly modelled with water - this could mean tsunami surges could travel further upstream than simulated, the “it would not be expected to cause significant extra inundation” (Lane et al. 2014, p.49)

***Table A2-1**. Distant source tsunami layer details*

Layer:	**Distant_Source_Tsunami_Modelling_Inundation** **Inundation Depth (m)**
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	http://gis.ecan.govt.nz/arcgis/services /Public/Distant_Source_Tsunami_Modelling_Inundation
Credit(s):	National Institute of Water and Atmospheric Research, Environment Canterbury
Reference(s):	Lane, E., Kohout, A., Chiaverini, A., & Jade, A. (2014). *Updated inundation modelling in Canterbury from a South American Tsunami*. Environment Canterbury report number R14/78. Christchurch, New Zealand.

Local Source Tsunami:

This layer combines coastal inundation modelling from two regional source tsunami scenarios:

1. a local-source tsunami generated by a moment magnitude 9.0 earthquake on the Hikurangi Subduction Zone, assuming the largest surge arrives at high tide.
2. a local-source tsunami generated by a moment magnitude 8.6 earthquake on the Wairarapa Fault, assuming the largest surge arrives at high tide.

Modelling software used: RiCOM.

Model Limitations:

- lower resolution bathymetry data in places introduces uncertainty errors
- Assumed fixed bathymetry / topography - coastal erosion by early tsunamis waves could increase inundation by subsequent tsunamis waves.

- Rivers were not explicitly modelled with water - this could mean tsunami surges could travel further upstream than simulated, the "it would not be expected to cause significant extra inundation" (Lane et al. 2014, p.49).
- The way in which the effect of building and land features on form drag is represented in the model is a source of uncertainty. Improving how this is represented is currently being researched by NIWA (Kohout 2015).

Table A2-2. *Regional source tsunami layer details*

Layer:	NIWA_Regional_Source_Tsunami_Combined_Inundation_2015 Inundation Depth (m)
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	http://gis.ecan.govt.nz/arcgis/services /Public/Tsunami_Regional_Source_Combined_Inundation
Credit(s):	National Institute of Water and Atmospheric Research, Environment Canterbury
Reference(s):	Kohout, A., Lane, E., Arnold, J., & Sykes, J. (2015). *Hikurangi Subduction Zone and Wairarapa Fault tsunami modelling for the Canterbury coast.* Environment Canterbury report number R15/130. Christchurch, New Zealand.

Map 2: Coastal Erosion Risk Map (LDRP110_MH2)

This map shows the modelled landward limit of the active beach system including any long-term rates of erosion to 2115 (100 years). Post-December 2011 earthquake LIDAR data was used.

Modelling approach: *Bruun rule* based building block approach.

Table A2-3. *Coastal erosion layer details*

Layer:	CoastalErosion.shp inland extent of erosionInundation Depth (m)
original coordinate system:	GD 1949 New Zealand Map Grid
Layer file source:	Jacobs
Credit(s):	Tonkin & Taylor, Christchurch City Council
Reference(s):	Tonkin and Taylor Ltd. (2015). *Coastal hazard assessment: Stage 2* (Vol. 851857.001). Christchurch, New Zealand. Retrieved from http://www.ccc.govt.nz/environment/land/coast/coastal-hazards/read-the-technical-report/ Appendix D: Sections 1, 2, 3, 6, 7, 8, 9.

Note: this map will be updated in 2017. In addition, a new ECAN coastal monitoring report for Pegasus Bay is currently being commissioned for 2017/18.

Map 3: Coastal Inundation Risk Map (LDRP110_MH3)

This map shows the modelled extent of future coastal inundation based on 100-year future projection (to 2015). Model output was first published in Figure 6.1 from Tonkin and Taylor (2015). Water levels represent 2015 high tide level of RL 2.4 m at Sumner Head. (2015 Highest Astronomical Tide of RL 1.4 m + 1.0 m sea level rise). Post-December 2011 earthquake LIDAR data was used.

Modelling approach: Bathtub and TUFLOW models applied to open and harbour coasts.

Table A2-4. *Coastal inundation layer details*

Layer:	CoastalInundation.shp inland extent of inundation (no depth information)
original coordinate system:	GD 1949 New Zealand Map Grid
Layer file source:	Jacobs
Credit(s):	Tonkin & Taylor, Christchurch City Council
Reference(s):	Tonkin and Taylor Ltd. (2015). *Coastal hazard assessment: Stage 2* (Vol. 851857.001). Christchurch, New Zealand. Retrieved from http://www.ccc.govt.nz/environment/land/coast/coastal-hazards/read-the-technical-report/

Note: this map will be updated in 2017. In addition, a new ECAN coastal monitoring report for Pegasus Bay is currently being commissioned for 2017/18.

Map 4: Groundwater Table Map (LDRP110_MH4)

Measured mean groundwater depth below surface, calculated using a 25m-grid Digital Elevation Model of the ground surface. Version 2 (2014) maps are based on monitoring from Sept 2010 to Nov 2013 reported in version 2 of the GNS Science report that describes how the maps were created (see reference below).

The groundwater table map did not encompass the whole catchment and so soil moisture (APAW at 1m) has been added to assist in extrapolation of the ground water table data in the upper catchment area, where blue indicates areas where soil moisture is very high (reasonably correlating with areas of small depth to ground water around Halswell) and yellow where soil moisture is very low (reasonably correlating with areas of large depth to ground water in the upper catchment). This is not an ideal solution - optimally groundwater table map would be extended to encompass the whole catchment, especially for sub-catchments 20, 21 and 22 (Hoon Hay Valley Stream and Hendersons Basin).

Measured data used: the depth of each surface beneath a 25m-grid Digital Elevation Model of the ground surface.

Table A2-5. *Groundwater table layer details*

Layer:	DepthToGroundwater_PostDec_MedianModel.tif inland extent of inundation (no depth information)
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	Canterbury Geotechnical Database (2014) "GNS Science Median Groundwater Surface Elevations", Map Layer CGD5160 - 10 June 2014, retrieved [17/11/2016] from https://canterburygeotechnicaldatabase.projectorbit.com/
Credit(s):	Tonkin & Taylor, Christchurch City Council
Reference(s):	van Ballegooy, S.; Cox, S. C.; Thurlow, C.; Rutter, H. K.; Reynolds, T.; Harrington, G.; Fraser, J.; Smith, T. (2014) Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake: Version 2, GNS Science Report 2014/18, April 2014. ISBN 978-1-927278-41-3. 79 p and 8 Appendices

Table A2-6. *Average soil moisture layer details*

Layer:	Soil Moisture - Average Profile Available Water at 1m average profile available water at 1m
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	Public/Landcare_SMap_Layers
Credit(s):	Landcare Research
Reference(s):	van Ballegooy, S.; Cox, S. C.; Thurlow, C.; Rutter, H. K.; Reynolds, T.; Harrington, G.; Fraser, J.; Smith, T. (2014) Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake: Version 2, GNS Science Report 2014/18, April 2014. ISBN 978-1-927278-41-3. 79 p and 8 Appendices

Map 5a: Earthquake: Vertical Ground Displacement Map (LDRP110_MH5a)

This maps shows vertical elevation changes between LiDAR data prior to the 4th September 2010 earthquake until after the 22nd February 2011 earthquake, approximating the vertical ground movements during significant earthquakes.

Vertical ground displacement contours were developed by Beavan et al. (2012) to incorporate vertical ground displacement for all earthquake events between (and including) 4th September 2010 and 23rd December 2011. Contours were supplied in .kmz format and so were converted to .kml in Google Earth before .kml to layer conversion in ArcGIS.

Vertical ground displacement raster layer was calculated from data obtained from the Geotechnical Database and manipulated in ArcGIS. The dataset which included all earthquakes from 4th September 2010 to 13th June 2012 has been presented as it covered significantly more of the catchment area and was very similar to the longer period dataset.

Table A2-7. *Vertical Ground Displacement contour layer details*

Layer:	4Sep-13Junvertdisp (polyline)
original coordinate system:	GCS WGS 1984
Layer file source:	Canterbury Geotechnical Database (2012) "Vertical Ground Surface Movements", Map Layer CGD0600 - 23 July 2012, retrieved [date] from https://canterburygeotechnicaldatabase.projectorbit.com/
Credit(s):	adapted from Beavan et al. (2012)
Reference(s):	Beavan, J., Levick, S., Lee, J. and Jones, K. (2012) Ground displacements and dilatational strains caused by the 2010-2011 Canterbury earthquakes, GNS Science Consultancy Report 2012/67. 59 p. https://www.nzgd.org.nz/ReportFiles/GNS/CR2012-067.htm

Table A2-8. *Vertical Ground Displacement (different between DEMs) layer details**

Layer:	TO BE IMPORTED (raster)
original coordinate system:	GCS WGS 1984
Layer file source:	Canterbury Geotechnical Database (2012) "Vertical Ground Surface Movements", Map Layer CGD0600 - 23 July 2012, retrieved [date] from https://canterburygeotechnicaldatabase.projectorbit.com/
Credit(s):	adapted from Beavan et al. (2012)
Reference(s):	Beavan, J., Levick, S., Lee, J. and Jones, K. (2012) Ground displacements and dilatational strains caused by the 2010-2011 Canterbury earthquakes, GNS Science Consultancy Report 2012/67. 59 p. https://www.nzgd.org.nz/ReportFiles/GNS/CR2012-067.htm

** this layer is yet to be sourced. However, it is available (though not downloadable) on the Geotech Database and so any reference to vertical ground displacement as a result of the Canterbury Earthquake Sequence refers to this.*

Map 5b: Earthquake: Liquefaction Susceptibility and Sep 2010 / Feb 2011 Occurrence Map (LDRP110_MH5b)

The map includes liquefaction from the September 2010 and February 2011 earthquake events & liquefaction susceptibility identified through Environment Canterbury's NHRP Liquefaction Study. This data is intended to provide regional guidance for TLA land use planners in discriminating land where damaging liquefaction is unlikely from areas where geotechnical investigation is needed to assess liquefaction hazard.

***Table A2-9**. Liquefaction susceptibility*

Layer:	**eastern-canterbury-liquefaction-susceptibility-2012.shp** *This dataset outlines areas predicted to be susceptible to liquefaction as defined in Figure 2.1, Brackley (2012). LIDAR topography data was limited to 10 m depth. The zones are primarily for use by territorial authorities to help them decide whether a separate geotechnical assessment relating to liquefaction is needed for development, and for subdivision and building permits to be granted.*
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	https://data.canterburymaps.govt.nz/layer/7539-eastern-canterbury-liquefaction-susceptibility-2012/
Credit(s):	Tonkin & Taylor, University of Canterbury, Environment Canterbury, Beca, Landcare Research, Lincoln University, Greg Curline, GNS Science.
Reference(s):	Figure 2.1 Brackley, H. L. (2012). *Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts.* Environment Canterbury report number R12/83. Christchurch, New Zealand.

***Table A2-10.** 4 September 2010 liquefaction occurrences*

Layer:	**liquefaction-occurrence-september-2010.shp** *Liquefaction mapping from aerial and satellite photos and site visit data following the Darfield (Canterbury) Earthquake of 4 September 2010, also incorporating data from external review comments.*
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	https://data.canterburymaps.govt.nz/layer/7548-liquefaction-occurrence-september-2010/
Credit(s):	Tonkin & Taylor, University of Canterbury, Environment Canterbury, Beca, Landcare Research, Lincoln University, Greg Curline, GNS Science.
Reference(s):	Figure A3.9 Brackley, H. L. (2012). *Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts.* Environment Canterbury report number R12/83. Christchurch, New Zealand.

Table A2-11. *22 February 2011 liquefaction occurrences*

Layer:	**liquefaction-occurrence-february-2011.shp** **Liquefaction mapping from aerial and satellite photos and site visit data following the Christchurch Earthquake of 22 February 2011, also incorporating data from external review comments.**
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	https://data.canterburymaps.govt.nz/layer/7547-liquefaction-occurrence-february-2011/
Credit(s):	Tonkin & Taylor, University of Canterbury, Environment Canterbury, Beca, Landcare Research, Lincoln University, Greg Curline, GNS Science.
Reference(s):	Figure A3.10 Brackley, H. L. (2012). *Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts.* Environment Canterbury report number R12/83. Christchurch, New Zealand.

Maps 6a and 6b: Soil Erosion and Mass Movements (LDRP110_MH6 and LDRP110_MH6b)

This map illustrates past erosion events (Map 6a) and mass movement risk (Map 6b) in the Ōpāwaho Heathcote Catchment.

Table A2-12. *Erosion type layer details (Map 6a)*

Layer:	**RecordedErosion** **represents a coverage where an erosion event has taken place. Includes erosion type, where recorded.**
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	CCC Web Feature Service (WFS) data feed
Credit(s):	Christchurch City Council
Reference(s):	n/a

Table A2-13. *High soil erosion risk area layer details (Map 6b)*

Layer:	**lwrp-high-erosion-risk-area.shp** **Where soil erosion risk areas are representative of those areas at high risk of tunnel gullying.**
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	https://data.canterburymaps.govt.nz/layer/7559-lwrp-high-erosion-risk-area/
Credit(s):	Canterbury Regional Council, Canterbury Maps
Reference(s):	n/a

Table A2-14. *High erosion risk area layer details (Map 6b)*

Layer:	Erosion Represents areas which have been assessed as being prone to an erosive process.
original coordinate system:	NZGD 2000 New Zealand Transverse Mercator
Layer file source:	CCC Web Feature Service (WFS) data feed
Credit(s):	Christchurch City Council
Reference(s):	n/a

Map 7a: Ōpāwaho Heathcote Sub-catchment Multi-Hazard Assessment (LDRP110_MH7a)

This map combined identified hazard risk areas across the Ōpāwaho Heathcote Catchment.

Layers:

1. Tsunami inundation layer
   Combined distant and regional tsunami inundation layers from Map 1.
2. Coastal erosion layer
   From Map 2.
3. Coast inundation layer
   From Map 3.
4. Depth to Groundwater layer
   Amended from Map 4 to show where water table <2m below surface.
5. Liquefaction Risk layer
   From Map 5b - this includes identified liquefaction areas, TC2 and TC3 zones and localities where liquefaction occurred during September 2010 and February 2011 earthquake events.
6. Erosion risk layer
   From Map 6.
7. Soil erosion risk layer
   From Map 6.

Map 7b: Ōpāwaho Heathcote Sub-catchments: Multi-Hazard Assessment Summary (LDRP110_MH7b)

This map summarises, in catalogue style, the hazards affecting each Ōpāwaho Heathcote sub-catchment. For details of spatial variation in hazard extents within each catchment, see Maps 1 to 6.